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A COMPARATIVE STUDY OF SPCTRAL2 AND SMARTS2 PARAMETERISED MODELS BASED ON SPECTRAL IRRADIANCE MEASUREMENTS AT VALENCIA, SPAIN

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Abstract—Results obtained using the parametric models SPCTRAL2 and SMARTS2 for the urban area of Valencia, Spain, have been analysed and compared with experimental measurements at ground level obtained with two Li-cor 1800 spectroradiometers with a 6 nm resolution. The study used two different input parameters in both models for the aerosol characterisation: the aerosol optical thickness at 0.5 μm, $\tau_{a\lambda(0.5)}$, and the Angstrom turbidity coefficient β. The results obtained show that both algorithms reproduce quite correctly the spectral irradiance experimental values when an urban aerosol model parameterised by the $\tau_{a\lambda(0.5)}$ value is considered. In all the cases the deviations are lower when SMARTS2 code is used.

1. INTRODUCTION

Atmospheric studies have always suffered from the impossibility of reproducing the atmosphere. It is not that something is wrong with the experiments or the techniques but rather that the atmosphere differs each time an experiment is repeated. Even computations of atmospheric properties suffer from the complement to this problem: different models assume different atmospheric conditions and so produce conflicting results. Standardised software can provide one solution to this problem, since there seems little advantage in computing more accurately than the accuracy with which one knows the atmosphere. Thus, a program of demonstrated reliability using standard algorithms for the different atmospheric effects is a boon to all (Kyle, 1991).

In this sense, a number of atmospheric algorithms have been described in the literature since the early ’80s. Such algorithms can be classified into two different groups: sophisticated rigorous codes (or radiative transfer codes, RTCs) and simple transmittance parameterisations (parameterised models, PMs).

For climate studies (Ramanathan *et al.*, 1983; Fouquart, 1987) and numerical weather forecast models (Morcrette, 1991) the rigorous codes at different levels are necessary. Reference radiation models, like line-by-line or narrow-band models are focused on the sensitivity of the calculation of radiation fields and the radiative cooling–heating rate on climate models. Examples of RTCs widely used by the scientific community are the codes: LOWTRAN 7 (Kneizys *et al.*, 1988), ZD-LOA (Fouquart and Bonnel, 1980; Fouquart *et al.*, 1991) and DOM (Stamnes *et al.*, 1988).

However, because of the detailed inputs needed, execution time, and some output limitations RTCs are not appropriate codes for many engineering applications. Most of the latter needs are currently filled by parameterised models that are relatively simple compared to RTCs using only a single homogeneous layer and a simple Beer’s law approach (Gueymard, 1995). For computerised engineering calculations, SPCTRAL2 (Riordan, 1994), based on Bird (1984) and Bird and Riordan (1986), and recently SMARTS2 (Gueymard, 1995), based on SMARTS (Gueymard, 1993), are the most frequently used.

In this work we compare the results provided by these two parameterised codes (SPCTRAL2 and SMARTS2) with the experimental results determined from spectral irradiance measurements, considering in particular the influence that the different aerosol models included in each algorithm have on the estimation. The comparison has been carried out by employing two different parameters in the aerosol characterisation: (1) the aerosol optical thickness, $\tau_{a\lambda}$, corresponding to 0.5 μm and obtained from direct spectral irradiance, and (2) the Angstrom turbidity coefficient β, obtained from integrated global and diffuse irradiance measurements.

2. THE PARAMETERISED MODELS

2.1. *The SPCTRAL2 model*

In 1984, Bird proposed a simple model to determine the spectral values of direct normal and diffuse horizontal irradiances (Bird, 1984). This model is based on parameterised models previously developed by Leckner (Leckner, 1978) and by Brine and Iqbal (1983). Subsequently, the model was used by Justus and Paris (1985) and by Bird and Riordan (1986). The latter authors, after making comparisons with experimental measurements and accurate spectral codes, introduced some corrections to give SPCTRAL2 model its present structure. The model is written in FORTRAN and can calculate punctual estimations of spectral irradiances employing as input parameters local geographic coordinates, precipitable atmospheric water vapour content, atmospheric pressure and aerosol optical thickness at 0.5 μm wavelength. The program used in this work was kindly provided by its author (Riordan, 1994), together with the TAPE2 file containing the extraterrestrial spectrum of Neckel and Labs (1981) and the absorption coefficients of water, ozone and homogeneous gases for 122 different wavelengths between 0.3 and 4.0 μm. The aerosol models available in the present version are: Maritime–Rural–Clear (MRC), Mean Rural (MR), Rural–Urban (RU), Mean Urban (MU) and Polluted–Urban (PU).

Recently Boscá *et al.* (1997) have proposed a modified version of this program, written in QB45 language and named ESPECT. This version is characterised by some innovations such as: (1) the incorporation of a method for the determination of the Angstrom coefficient β that is based on global and diffuse integrated irradiance values (Pinazo *et al.*, 1995); and (2) the use of different values for the parameters of the aerosol models implemented in the code (forward scattering, Fc; aerosol single scattering albedo, ω_0; Angstrom's exponent, α; aerosol asymmetry factor, $\langle\cos\theta\rangle$; single scattering albedo at 0.4 μm, $\omega_{0.4}$), in accordance with those proposed by Angstrom (1964), Katz *et al.* (1982), Gueymard (1989), Iqbal (1983) and Justus and Paris (1987). In this paper, a FORTRAN version of this program has been used. Therefore when the SPCTRAL2 model is mentioned in what follows, it must be understood that it is actually a modified SPCTRAL2 code in the above mentioned sense. Table 1 presents the characteristic values of the parameters for determining β using the five different aerosol models implemented in this code.

2.2. *The SMARTS2 model*

The SMARTS2 model (Simple Model for the Atmospheric Radiative Transfer of Sunshine) was proposed by Gueymard in 1995 (Gueymard, 1995). It is based upon an extensive revision of the algorithms used to calculate direct beam radiation with the spectral model SMARTS (Gueymard, 1993) and consists of a separate parameterisation of the different extinction processes involved in the atmosphere. To obtain this, more accurate transmittance functions for all atmospheric extinction processes are introduced and the effects of temperature and humidity are considered. The model also includes very accurate absorption coefficients derived from spectroscopic data. The extraterrestrial spectrum uses a total of 1881 wavelengths between 0.28 and 4.020 μm giving a higher resolution for engineering use. The output can then be downgraded according to the user's needs. A detailed description of the parameterisation of the different atmospheric components may be found in Gueymard (1995). The version used in this work was kindly provided by its author and corresponds to his latest revised version (Gueymard, 1997).

SMARTS2 code allows the introduction of ground meteorological data or the choice of 10 different reference atmospheres if ground data are not available. It also allows the choice of

Table 1. Characteristic parameters of the different aerosol models for SPCTRAL2

Model	Fc	ω_0	α	$\langle\cos\theta\rangle$	$\omega_{0.4}$
MRC	0.78	0.94	1.4	0.60	0.96
MR	0.81	0.90	1.3	0.65	0.95
RU	0.84	0.81	1.3	0.70	0.64
MU	0.84	0.74	1.2	0.70	0.64
PU	0.87	0.59	1.1	0.75	0.74

Fc: forward scattering; ω_0: aerosol single scattering albedo; α: Angstrom's exponent; $\langle\cos\theta\rangle$: aerosol asymmetry factor; $\omega_{0.4}$: single scattering albedo at 0.4 μm.

nine predefined aerosol models or the introduction of a different model proposed by the user. The aerosol models available in the present version are: (1) four proposed by Shettle and Fenn (1979)—rural (SFR), urban (SFU), maritime (SFM) and tropospheric (SFT); (2) two proposed by Braslau and Dave (1973)—BD-C (aerosol type C) and BD-C1 (aerosol type L); and (3) three corresponding to the Standard Radiation Atmosphere (SRA) (WMO, 1986)—continental (SC), urban (SU) and maritime (SM).

To compare theoretical data with experimental data, Gueymard (1995) shows the importance of taking into account the circumsolar diffuse radiation that is also intercepted in the aperture of an actual spectroradiometer, sun photometer or pyrheliometer. This circumsolar contribution increases with turbidity and optical mass, and decreases sharply with the angular distance from the sun's centre. Because the circumsolar irradiance from the sky is not negligible compared to the sun's direct beam irradiance, at least in some conditions, a correction factor needs to be applied to the calculated spectral beam irradiance if a radiometer with a field of view larger than the solar disk is to be simulated. The SMARTS2 model introduces a correction in order to consider this circumsolar contribution.

3. EXPERIMENTAL SET-UP AND METHODOLOGY

The spectral solar irradiance measurements were obtained using two Li-cor 1800 spectroradiometers. The spectral band of these instruments ranges from 300 to 1100 nm, with a 6 nm bandwidth. The characteristic and calibration protocol of these instruments and the measurement procedure are detailed elsewhere (Cachorro *et al.*, 1997; Myers, 1989; Riordan *et al.*, 1989). These authors recognise that the calibration curves obtained from such spectroradiometers (using a reference lamp) showed a deviation lower than 5% for wavelengths higher than 400 nm. For shorter wavelengths this deviation increases gradually, attaining a maximum in the UVB range (Martínez-Lozano *et al.*, 1995). The two instruments used in this work produce highly comparable results under varying conditions. Figure 1 presents an example of the direct irradiance spectral curves obtained by each instrument for different optical air masses on 12 February 1997, six months after

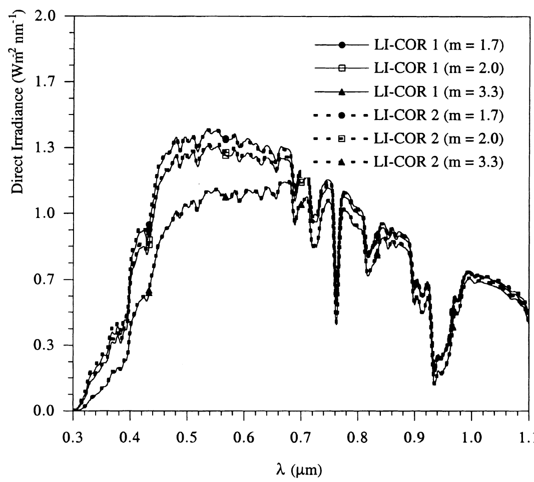

Fig. 1. Comparison between the experimental direct irradiance measurements obtained with the two Li-cor 1800 spectroradiometers for different optical air mass values. Day: 12 February 1997.

the calibration indoors using a reference lamp. During the three months of the measurement campaign, the deviations were never greater than those shown in Fig. 1.

Global and direct normal integrated irradiances were continually recorded by means of Kipp-Zonen CM-11 pyranometers and Eppley NIP pyrheliometers, respectively. The instrumentation used constitutes part of two solar radiation measuring stations described in previous papers (Utrillas *et al.*, 1991; Pinazo *et al.*, 1995). The measurements of integrated irradiance serve two different functions: (1) they confirm the persistence (if any) of atmospheric conditions during the measurement time, and (2) they allow a characterisation of atmospheric conditions through the indices k_t (ratio between the extraterrestrial global irradiation and the global irradiation at ground level on a horizontal surface), k_n (the same as k_t, but referring to direct irradiation at normal incidence) and β, the Angstrom turbidity coefficient.

Direct measurements of atmospheric temperature and average daily temperature at ground level were also carried out. The water vapour content was estimated from relative humidity measurements, because no direct measurements were available. As we had neither measurements of the aerosol asymmetry parameter nor of the aerosol single scattering albedo, the aerosol models proposed by the two algorithms were used, five corresponding to SPCTRAL2, and nine to SMARTS2.

The spectral irradiance dataset obtained from the experimental measurements have been compared with those predicted by SPCTRAL2 and SMARTS2 models. In order to be able to strictly compare the results it has been necessary to downgrade the experimental values in the case of SPCTRAL2. For SMARTS2 on the contrary, the results of the estimation have been smoothed to the field of view and bandpass of the instrument. SMARTS2 possesses a post-processor that scans the raw outputs (transmittances and irradiances) and smooths them to derive new outputs depending on the user's needs. The code allows the instrumental characteristics to be approximated by either a Gaussian or a triangular function with a known full width at half maximum. The Gaussian approximation has been employed in both downgrading processes.

To obtain the results predicted by the algorithms, two different aerosol parameters have been used in both cases: (1) the value of the aerosol optical thickness at 0.5 μm, $\tau_{a\lambda(0.5)}$, as obtained from the experimental direct irradiance measurements used for the analysis; and (2) the value of the Angstrom turbidity coefficient, β, obtained from experimental measurements of integrated direct and global irradiance. This second parameter was considered because spectral data at ground level are frequently not accessible, whereas there is a wide net of stations with integrated measurements which make it easy to obtain adequate values of β.

From the spectral measurements at normal incidence, $\tau_{a\lambda(0.5)}$, values were deduced by using the Beer law to obtain the total optical thickness for all the different atmospheric extinction processes, $\tau_{T\lambda}$. Once the total atmospheric optical thickness had been determined, the value of the aerosol optical thickness, $\tau_{a\lambda}$, is obtained by removing from the total transmittance the contributions due to Rayleigh scattering and to absorption by the other atmospheric components. The Rayleigh optical thickness was calculated from its theoretical expression with the improvements proposed by Gueymard (1995). For the 0.5 μm wavelength, the ozone absorption coefficient from Anderson and Mauersberger (1992) was assumed and, for the ozone content, we considered the measurements taken in Madrid by the INM (Instituto Nacional de Meteorología) using a Brewer spectroradiometer (Cisneros, 1996). The NO_2 absorption coefficients from Davidson *et al.* (1988), and the effective path lengths of the NO_2 for Mid Latitude Winter proposed by LOWTRAN 7 code (Kneizys *et al.*, 1988) were used.

The β value was obtained from direct normal integrated irradiance data and from diffuse global integrated irradiances on a horizontal surface using the method proposed by Pinazo *et al.* (1995). This method needs as input parameters only the diffuse and the global irradiances on a horizontal surface, besides the dimensionless parameters associated with the corresponding atmosphere type.

In order to analyse the deviation of the estimated values obtained by both models from the experimental values, two different error estimators have been used: RMSD (root mean square deviation) and MBD (mean bias deviation). These are statistical estimators which are commonly used for evaluating the accuracy of models. RMSD always gives positive values whilst MBD, defined as modelled minus observed, may be positive or negative, the positive values corresponding to overestimation by the model. Although solar irradiance papers usually use absolute values when evaluating errors we have used relative values in order to better compare results (Kambezidis *et al.*, 1994; Martínez-Lozano and Utrillas, 1995).

4. RESULTS AND DISCUSSION

The values estimated by SPCTRAL2 and SMARTS2 have been compared with those corresponding to 60 datasets of spectral direct irradiance at normal incidence registered at Valencia, corresponding to 10 cloudless days in the period January–March 1997. As has been stated previously, the analysis of the deviations has considered the mean relative values of the RMSD and of the MBD in the interval 0.3–1.1 μm. In the case of SPCTRAL2 these mean values have been obtained from 66 spectral values, whereas for SMARTS2, 801 spectral values have been used.

We limited the analysis of the results to establishing of analogies between the spectral values of the experimental direct irradiance and those obtained by the models. The results obtained for the five aerosol models included in SPCTRAL2 and the nine aerosol models included in SMARTS2 have been considered.

4.1. *Estimated values using* $\tau_{a\lambda(0.5)}$

Using the methodology described above, we obtained the values of the aerosol optical depth at 0.5 μm from the solar irradiance spectra. The value of $\tau_{a\lambda(0.5)}$ was introduced to the SPCTRAL2 and SMARTS2 codes in order to characterise the different aerosol models. Tables 2 and 3 summarise the deviations between the theoretical and the experimental spectral irradiance values for the different aerosol models. They show the maximum, minimum and average MBD and RMSD as well as the standard deviation, mean deviation and standard error. Table 2 refers to SPCTRAL2 whilst Table 3 refers to SMARTS2.

Table 2. Statistical characteristics of the deviations (MBD and RSMD) between experimental and modelled SPCTRAL2 values of the spectral irradiance for the different aerosol models, considering $\tau_{a\lambda(0.5)}$ as input parameter

			MBD (%)			
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
MRC	19	−3.5	2.0	4.7	3.1	0.9
MR	19	−3.7	2.0	4.7	3.2	0.9
RU	19	−3.7	2.0	4.7	3.2	0.9
MU	19	−3.8	1.9	4.8	3.2	0.9
PU	20	−3.9	1.9	4.9	3.3	0.9
			RSMD (%)			
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
MRC	5.4	29	9.8	5.3	3.6	1.0
MR	5.2	28	9.6	5.3	3.5	1.0
RU	5.2	28	9.6	5.2	3.5	1.0
MU	5.1	28	9.5	5.0	3.4	1.0
PU	5.1	28	9.5	4.9	3.3	0.9

Mn: minimum; *Mx*: maximum; *M*: arithmetic mean; σ: standard deviation; $\bar{\sigma}$: mean deviation; *StdE*: standard error.

Table 3. Statistical characteristics of the deviations (MBD and RSMD) between experimental and modelled SMARTS2 values of the spectral irradiance for the different aerosol models, considering $\tau_{a\lambda(0.5)}$ as input parameter

			MBD (%)			
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
SFR	2.7	−0.4	0.9	0.7	0.5	0.1
SFU	2.1	−1.6	−0.0	0.9	0.7	0.2
SFM	0.9	−8.4	−2.8	2.5	1.9	0.5
SFT	8.4	1.6	4.0	1.5	1.1	0.3
SC	2.5	−0.9	0.4	0.8	0.6	0.2
SU	2.7	−0.5	0.8	0.7	0.5	0.1
SM	−0.4	−10	−4.4	2.8	2.2	0.5
BD-C	0.2	−7.0	−3.1	2.1	1.6	0.4
BD-C1	0.3	−6.9	−3.0	2.0	1.6	0.4
			RSMD (%)			
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
SFR	2.9	12	6.0	2.2	1.7	0.4
SFU	3.2	13	6.7	2.5	2.1	0.5
SFM	4.2	23	11	5.3	4.5	1.0
SFT	3.1	12	6.6	2.4	1.9	0.5
SC	3.0	12	6.0	2.2	1.7	0.4
SU	2.7	12	5.4	2.1	1.6	0.4
SM	5.1	25	13	5.8	4.9	1.1
BD-C	5.9	30	15	7.0	5.9	1.4
BD-C1	5.8	30	15	7.0	5.9	1.4

Mn: minimum; *Mx*: maximum; *M*: arithmetic mean; σ: standard deviation; $\bar{\sigma}$: mean deviation; *StdE*: standard error.

The mean MBD showed that the aerosol models included in SPCTRAL2 led to an underestimation of about 2% of the experimental values, whilst in SMARTS2 code a set of models (SFR, SFT, SC, SU) underestimated the experimental values whilst all the others overestimate them. It is also possible to observe that the standard deviation, the mean deviation and the mean error values were lower in SMARTS2 models than in SPCTRAL2 ones, meaning that the variation range of the MBD mean values was lower in the latter case.

The mean RMSD values show that the differences among the mean deviations associated with the different aerosol models implemented in SPCTRAL2 were low (between 9% and 10% approximately). This result may be explained by considering that the standard values of the different parameters presented in Table 1 are mainly used to determine diffuse radiation. The only term that is used to determine the spectral direct irradiance by the algorithm is the α value, which varies only between 1.1 and 1.3. As for SMARTS2, the mean value of the RMSD oscillated between 5% and 15% depending on the aerosol model employed, meaning that there is a set of aerosol models, among those implemented in this algorithm, that do not reproduce the atmospheric conditions of Valencia correctly . However, there are several other aerosol models implemented in the algorithm with a mean RMSD value of about 7%, and an associated standard deviation of about 2%. Because the results for the urban and rural/continental models are so close, it may indicate that Valencia experiences a mix of rural and continental aerosols in the background and of locally produced urban aerosols. Moreover, it is probable that the relative concentrations of these different aerosols vary over time. Nevertheless, as a first approximation, we have used the aerosol models predefined in the algorithm in order to simplify the problem. A more detailed data analysis would constitute a more discriminant and refined test in the comparison between SPCTRAL2 and SMARTS2, but goes beyond the scope of this paper.

In order to systematise the results, the possible relation with the optical air mass, m, and with the aerosol optical thickness at 0.5 μm,

$\tau_{a\lambda(0.5)}$, have been investigated. The evolution of the RMSD with the optical air mass of each of the aerosol models included in both algorithms, SPCTRAL2 and SMARTS2 are shown in Fig. 2. For SPCTRAL2 (Fig. 2(a)) there existed a clear dependence of the RMSD values on the optical mass, both increasing simultaneously. Furthermore, the variation of the RMSD with the optical air mass was practically independent of the aerosol model used. This could be because of the reason previously mentioned: the only factor that is considered in the calculation of the direct irradiance by SPCTRAL2 is the Angstrom wavelength exponent α whose values ranges between 1.1 and 1.3 (Table 1). Figure 2(a) shows that the deviations between the values estimated by the models and the experimental ones oscillated between 5% and 28%, the extreme values corresponding to optical air masses of 1.4 and 3.9, respectively. The corresponding MBD, not included in the figure, was systematically negative in the morning and positive in the afternoon, with extreme values −4% (air mass 1.4) and 20% (air mass 3.9). This fact could be explained on the basis that SPCTRAL2 uses a fixed α value for each predefined aerosol model, as can be seen in Table 1. In this sense, possible variations of aerosols size along a day, not accounted for in the model, could give place to over/under estimation of the modelled irradiance. Our results for MBD seem to point out that α decreases in the afternoon for all the days with available experimental data. This fact can be explained taking into account the proximity of Valencia to the sea, which could lead to a hygroscopic growing of aerosols. Considering SMARTS2 (Fig. 2(b)) the relation between the RMSD and the optical air mass is not so evident. It is possible to classify the models into two different groups. One including the maritime models (S&F and SRA) and the models of Braslau and Dave and the other group containing all the other models. This second group showed lower deviations from the experimental data with smaller optical air mass, whereas the RMSD increased slightly (between 5% and 11%) with increasing values of m. The models in the first group presented higher deviations, even for small values of m.

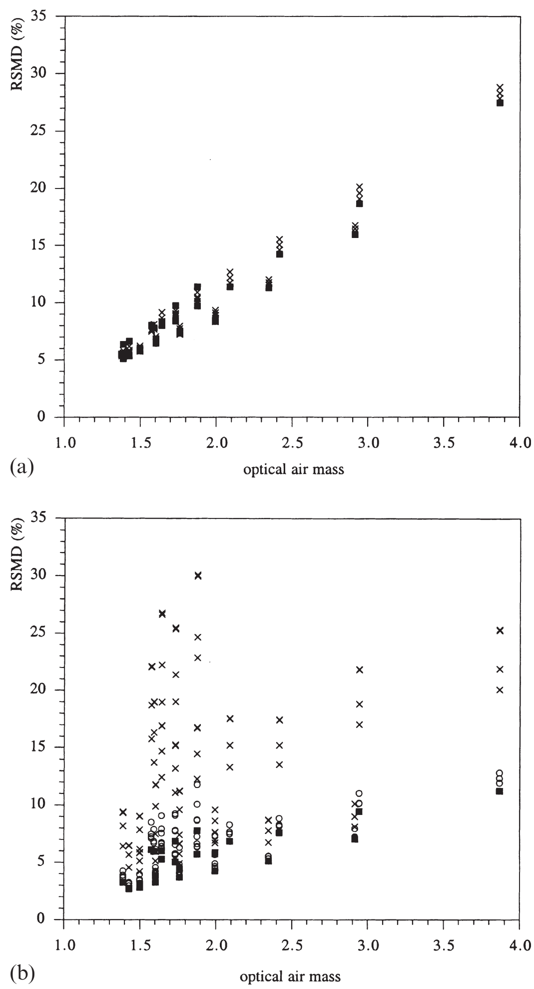

Fig. 2. Evolution of RMSD with the optical air mass taking $\tau_{a\lambda(0.5)}$ as input parameter. (a) SPCTRAL2 code: PU aerosol model (●); other aerosol models (○). (b) SMARTS2 code: SU aerosol model (●); SFR, SFU, SFT and SC aerosol models (○); SFM, SM and Braslau and Dave aerosol models (×).

A similar analysis considered the possible relation of the error indices with the $\tau_{a\lambda(0.5)}$ value. Figure 3 presents the evolution of the mean relative values of the RMSD and MBD obtained for the aerosol models included in SPCTRAL2 and SMARTS2. For SPCTRAL2 the RMSD values increased if $\tau_{a\lambda(0.5)}$ decreased (Fig. 3(a)). For very low turbidity conditions, the extinction processes of atmospheric constituents other than aerosols, as for example the NO_2 absorption (not accounted for by the model), become relatively more important. This fact could justify the high error values associated with $\tau_{a\lambda(0.5)}$. Moreover, the instrumental noise becomes more noticeably at low optical thickness and could also contribute to increase these error values. Figure 3(a) also shows that for low turbidity conditions the MBD was positive indicating an underestimation of the experimental values. Figure 3(b) and 3(c) show, respectively, the evolution with $\tau_{a\lambda(0.5)}$ of relative MBD and RMSD for the aerosol models included in SMARTS2. The MBD values represented in Fig. 3(b) confirm what was previously

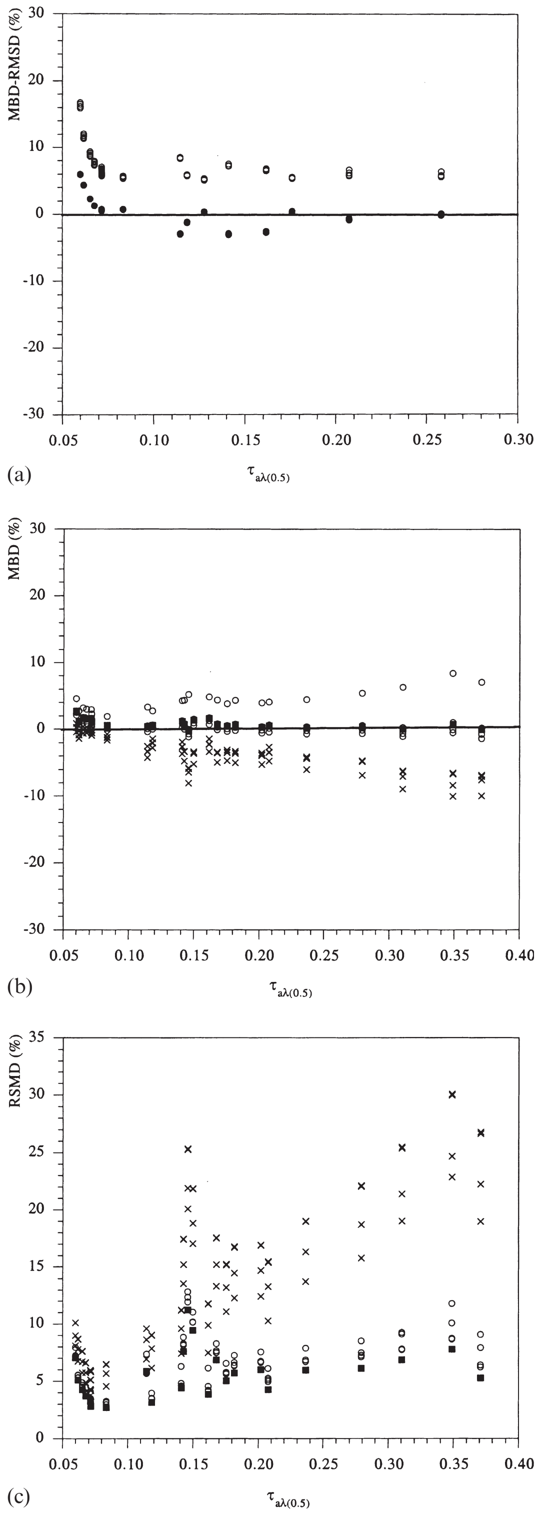

Fig. 3. Evolution of MBD and RMSD with $\tau_{a\lambda(0.5)}$ taking $\tau_{a\lambda(0.5)}$ as input parameter. (a) MBD (●) and RMSD (○) for SPCTRAL2 code. (b) MBD for SMARTS2 code: SU aerosol model (●); SFR, SFU, SFT and SC aerosol models (○); SFM, SM and Braslau and Dave aerosol models (×). (c) RMSD for SMARTS2 code: SU aerosol model (●); SFR, SFU, SFT and SC aerosol models (○); SFM, SM and Braslau and Dave aerosol models (×).

considered. The maritime aerosol models and the model of Braslau and Dave overestimated the experimental values while the other models had very low MBD values showing no definite tendency. In Fig. 3(c) (RMSD) it is possible to observe again two different groupings of the models relating to the optical air mass as described above: most of the models show deviations that are practically constant and independent of the $\tau_{a\lambda(0.5)}$ value, while the other models present increasing deviations (from 9% to 30% approximately) with increasing values of $\tau_{a\lambda(0.5)}$.

4.2. Estimated values using β

Using the methodology described above, we obtained the values of the Angstrom turbidity coefficient β, from the available hourly values of global and diffuse broad band irradiance. Using this coefficient, the values estimated by SPCTRAL2 and SMARTS2 were recalculated repeating the process previously described and comparing the new results with the experimental values. The results, as summarised in Table 4 (SPCTRAL2) and Table 5 (SMARTS2) were similar to those presented in Tables 2 and 3.

The MBD values showed that, on average, SPCTRAL2 code overestimated the experimental values independently of the aerosol model used, the contrary of what happened when $\tau_{a\lambda(0.5)}$ was taken as an input variable. SMARTS2 code, on the other hand, underestimated the experimental values except when the

Table 4. Statistical characteristics of the deviations (MBD and RSMD) between experimental and modelled SPCTRAL2 values of the spectral irradiance for the different aerosol models, considering β as input parameter

	MBD (%)					
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
MRC	−2.9	−25	−10	6.3	5.1	1.2
MR	−2.9	−26	−11	6.5	5.2	1.2
RU	−0.2	−23	−8.9	6.0	4.8	1.2
MU	2.8	−20	−7.4	5.8	4.5	1.1
PU	12	−15	−3.1	5.9	4.1	1.1
	RSMD (%)					
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
MRC	7.6	29	16	5.9	4.8	1.1
MR	7.6	31	16	6.2	5.0	1.2
RU	7.1	27	14	5.4	4.4	1.0
MU	6.7	24	14	5.0	4.2	1.0
PU	5.8	23	11	4.4	3.6	0.8

Mn: minimum; *Mx*: maximum; *M*: arithmetic mean; σ: standard deviation; $\bar{\sigma}$: mean deviation; *StdE*: standard error.

Table 5. Statistical characteristics of the deviations (MBD and RSMD) between experimental and modelled SMARTS2 values of the spectral irradiance for the different aerosol models, considering β as input parameter

Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
			MBD (%)			
SFR	9.9	−10	1.1	3.9	2.7	0.7
SFU	13	−4.7	3.7	3.6	2.5	0.7
SFM	28	3.5	10	6.1	4.6	1.2
SFT	0.0	−32	−11	7.2	5.3	1.4
SC	11	−8.2	2.0	3.7	2.6	0.7
SU	8.6	−12	0.3	4.0	2.8	0.8
SM	31	4.4	12	6.5	5.0	1.2
BD-C	33	4.6	13	6.9	5.3	1.3
BD-C1	33	4.7	13	6.9	5.4	1.3
			RSMD (%)			
Model	*Mn*	*Mx*	*M*	σ	$\bar{\sigma}$	*StdE*
SFR	2.8	19	7.0	3.6	2.6	0.7
SFU	4.1	23	9.3	4.5	3.2	0.9
SFM	6.5	42	18	10	8.2	1.9
SFT	3.9	40	15	8.1	5.9	1.6
SC	3.2	20	7.6	3.8	2.7	0.7
SU	2.5	17	6.4	3.4	2.5	0.7
SM	7.8	46	20	11	8.8	2.1
BD-C	8.3	50	22	12	9.6	2.3
BD-C1	8.3	50	22	12	9.6	2.3

Mn: minimum; *Mx*: maximum; *M*: arithmetic mean; σ: standard deviation; $\bar{\sigma}$: mean deviation; *StdE*: standard error.

tropospheric aerosol model SFT was considered. As to the RMSD, its values were higher than those obtained when considering $\tau_{a\lambda(0.5)}$. The RMSD demonstrated two characteristics: Firstly, the use of β permitted a better differentiation between the different aerosol models implemented in SPCTRAL2. In the case of $\tau_{a\lambda(0.5)}$ the mean deviations oscillated between 9% and 10% whilst here they oscillated between 11% and 16% the polluted–urban model being the one that introduced the lower deviations. This higher dispersion may be explained by considering that all the parameters described in Table 1 contribute to the calculations of the Angstrom turbidity coefficient. Secondly, and referring to the SMARTS2 model, two different groups of aerosol models with clearly different behaviours were observable, but the tropospheric model SFT presented here had worst results with mean RMSD reaching 15%.

The relation of MBD and RMSD to the optical air mass was similar to that described for $\tau_{a\lambda(0.5)}$. Since in this case the input parameter used in the aerosol parameterisation is the turbidity coefficient β, the MBD and RMSD as functions of this coefficient have been analysed. The deviations from the integrated direct irradiance at normal incidence were studied instead. Figure 4 shows the deviations for SPCTRAL2 and SMARTS2. In both cases the errors increased generally with decreasing direct irradiance. For SPCTRAL2, the polluted–urban aerosol model was the one with the lower deviations from the experimental data, with a relative RMSD between 6% and 23%. Figure 4(b) (SMARTS2) shows the different behaviour of the aerosol models described above. In this case it was the SRA urban model (SU) that presented the best results, with deviations from the experimental data of between 2.5% and 17%.

4.3. Comparison between the two algorithms

Since SPCTRAL2 and SMARTS2 do not use the same aerosol models, it is not possible to

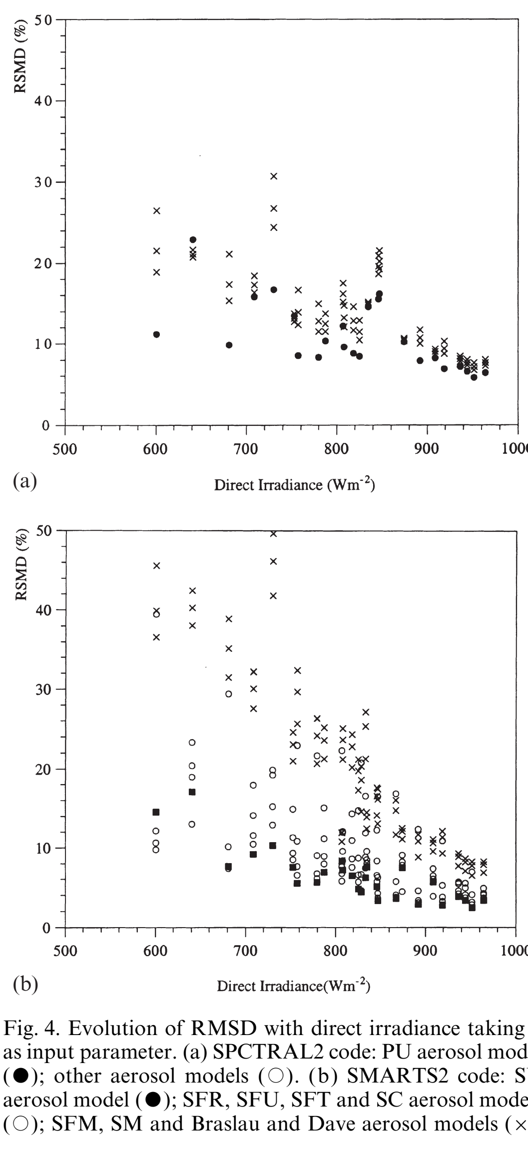

Fig. 4. Evolution of RMSD with direct irradiance taking β as input parameter. (a) SPCTRAL2 code: PU aerosol model (●); other aerosol models (○). (b) SMARTS2 code: SU aerosol model (●); SFR, SFU, SFT and SC aerosol models (○); SFM, SM and Braslau and Dave aerosol models (×).

perform a strict comparison between the two algorithms from the available experimental data. Nevertheless, it is possible to establish which algorithm, with the appropriate predefined aerosol model, is the one with lower deviations from the experimental direct irradiance values measured at Valencia. Obviously, if a variable aerosol model defined for the particular atmospheric characteristics of Valencia was available, it could be possible to carry out a more accurate comparison.

Considering the previous results, it can be concluded that if $\tau_{a\lambda(0.5)}$ is employed as an input parameter for the aerosols characterisation, the best aerosol model used by SPCTRAL2 for the urban area of Valencia is the polluted urban one. As for SMARTS2 the aerosol model leading to lower deviations is the SRA urban model although others produce similar results. In Fig. 5 the mean RMSD values of the direct spectral irradiance of these models, obtained from Fig. 3, is represented as a function of m. It shows that SMARTS2 models offer values that are always lower than SPCTRAL2 with the differences increasing with the optical mass.

If the Angstrom turbidity coefficient is used for the aerosol characterisation, the aerosol models that best reproduce the spectral direct irradiance for Valencia are again the urban model of the SMARTS2 code and the polluted–urban model of the SPCTRAL2 code. The mean values of the RMSD corresponding to the spectral direct irradiance for each model, as a function of the integrated direct irradiance, obtained from Fig. 4, are presented in Fig. 6. Similarly to the $\tau_{a\lambda(0.5)}$ case, SMARTS2 presented lower deviations than SPCTRAL2, although the differences between them became very small for higher values of direct irradiance.

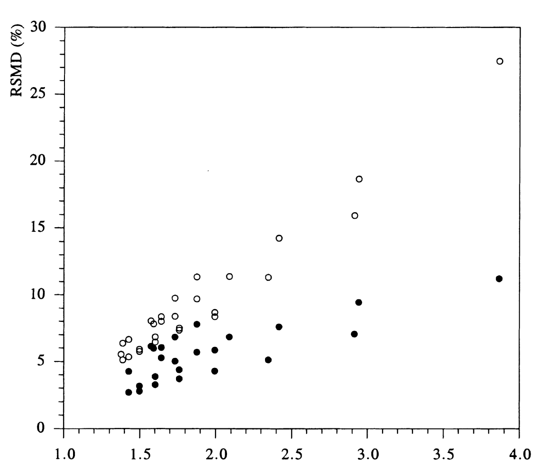

Fig. 5. Comparison between SPCTRAL2 with PU aerosol model (○) and SMARTS2 with SU model (●) RMSD taking $\tau_{a\lambda(0.5)}$ as input parameter.

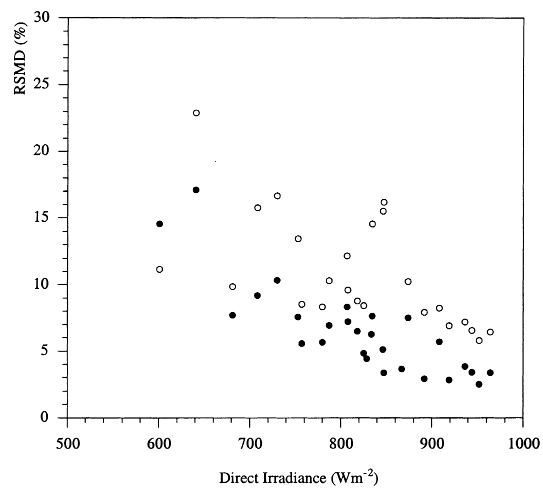

Fig. 6. Comparison between SPCTRAL2 with PU aerosol model (○) and SMARTS2 with SU model (●) RMSD taking β as input parameter.

As an example, in Fig. 7 one of the experimental spectra employed in the analysis corresponding to 11 March 1997 and an optical air mass of 1.4 is presented. The estimated spectra with the lower deviations from the experimental values, the polluted urban of SPCTRAL2 and the SRU of SMARTS2, are also shown in Fig. 7. In both cases the input parameter for the aerosol characterisation was $\tau_{a\lambda(0.5)}$. In order to make a more detailed analysis of the spectral behaviour of these models, the spectrum was divided into three zones: 0.3–0.5 μm (Fig. 7(a)), 0.5–0.7 μm (Fig. 7(b)) and 0.7–1.1 μm (Fig. 7(c)). SMARTS2 and SPCTRAL2 compare well and are relatively similarly to the measured data (considering the lower resolution and lack of smoothing of the latter model). However, SMARTS2 compares significantly better in the 0.5–0.7 μm interval, and reproduced the different atmospheric components' absorption bands best, even those corresponding to the water vapour and to the oxygen in the near infrared.

5. CONCLUSIONS

The results obtained for the urban area of Valencia, Spain by the parametric models SPCTRAL2 and SMARTS2 have been analysed. They have been compared with experimental measurements at ground level obtained with 6 nm resolution Li-cor 1800 spectroradio-

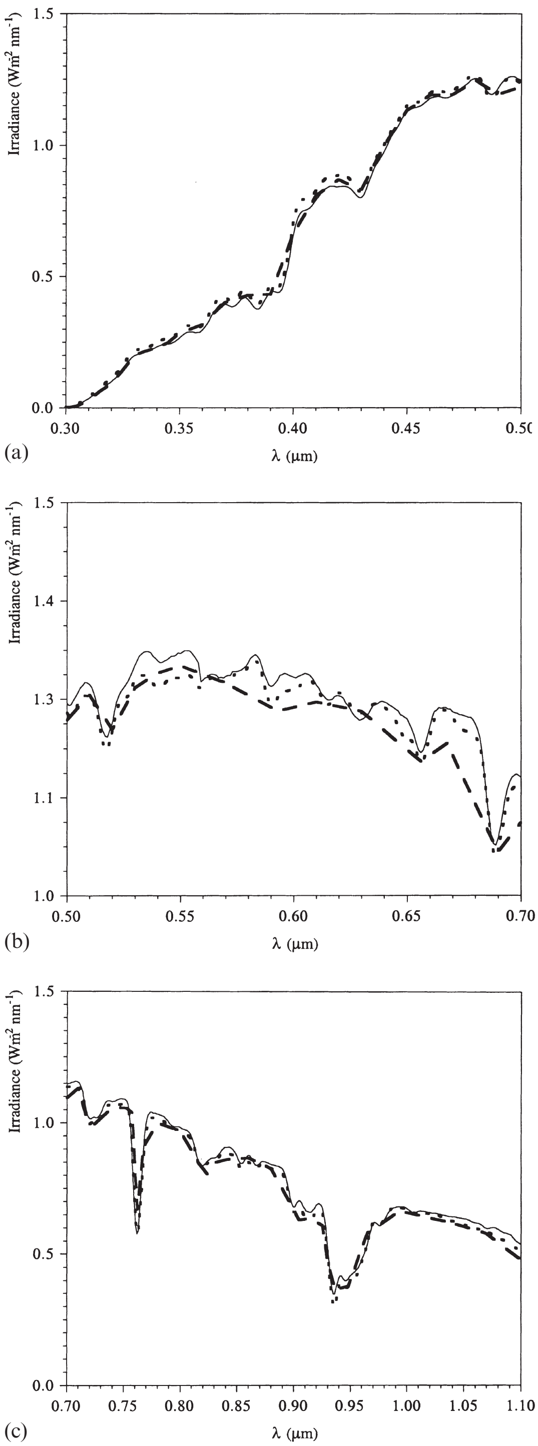

Fig. 7. Comparison between the spectral irradiances, experimental (——) and estimated by the SPCTRAL2 (- - -) and SMARTS2 (· · ·) codes. (a) 0.3–0.5 μm, (b) 0.5–0.7 μm, (c) 0.7–1.1 μm. Note the different range for the y axis in the figures.

meters. The study used two different parameters for the aerosol characterisation of each model: the aerosol optical thickness at 0.5 μm, $\tau_{a\lambda(0.5)}$, and the Angstrom turbidity coefficient β. In order to analyse the deviation of the estimated values produced by both models from the experimental ones, two different error estimators were used: RMSD (root mean square deviation) and MBD (mean bias deviation).

If the input parameter for the aerosol characterisation is $\tau_{a\lambda(0.5)}$, SPCTRAL2 code presents values of the relative RMSD of about 10%, it being impossible to choose between the aerosol models implemented in the algorithm. SMARTS2 code presents relative RMSD values between 5% and 15% depending on the aerosol model considered, with the SRA urban model being the one with the lower deviations.

If the input parameter for the aerosol characterisation is β, the deviations of both algorithms increase. In the best cases these deviations are about 11% for SPCTRAL2 code (polluted–urban aerosol model) and 6% for SMARTS2 code (SRA urban aerosol model).

Both algorithms are easy to operate and all the parameters they require are accessible, especially if the aerosol turbidity coefficient is employed. Thus, they are highly applicable for the study of energetic gains. Nevertheless, the SMARTS2 model employs more updated constants and parametric functions. Furthermore this model has a higher resolution and presents lower deviations in this analysis, so it is more interesting for theoretical simulations if the aerosol model is adequate.

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